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Abstract. Small-tilt micromirror-based 2×2 fiber optic switch array structures are proposed using fixed mirrors and fiber interconnections. A multiwavelength 2×2 fiber optic switch based on this small-tilt micromirror is experimentally demonstrated. The key innovation in this architecture is the use of a specially located fixed mirror to form a symmetric 2×2 retroreflective switching structure. These 2×2 fiber optic switch structures can also provide a fault-tolerant design using a macropixel approach. A two-dimensional digital micromirror device (2D-DMD) from Texas Instruments (TI) designed to operate in the visible band is used to represent the small-tilt micromirrors in our experimental demonstration. Multiwavelength switch operation is characterized by changing the operating wavelength of the tunable laser. The measured average optical coherent crosstalk is -22 dB with ± 0.9 dB fluctuation over 40 nm, limited by the on-off ratio of the 2D-DMD. The measured average optical loss is 14.8 dB at a 1.55-μm operating wavelength, limited by the visible wavelength design TI 2D-DMD, three-port optical circulators, fiber adapters, and free-space-to-fiber coupling efficiency. [S0091-3286(00)02002-X]

Subject terms: fiber optics; mirrors; microelectromechanical systems (MEMS).

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1 Introduction

Optical switches are important for constructing flexible and reliable optical transmission systems and optical signal processing systems because they offer low weight and immunity to electromagnetic interference, and eliminate the need for optical-to-electrical and electrical-to-optical conversion at the switch. The most mature commercially available fiber optic switch is based on optomechanical movement[1] and has the advantages of polarization independence, low loss, and high interchannel isolation. Nematic liquid crystal (NLC)-based fiber optic switch was also demonstrated, resulting in low optical interchannel crosstalk of -35 dB and a limited switching speed in tens of milliseconds domain.[2] Recently, a ferroelectric liquid crystal (FLC)-based fiber optic switch was demonstrated, providing an optical interchannel crosstalk of -34.13 dB and a faster 35-μs switching speed.[3] Nevertheless, for large-scale network switching, these approaches are perhaps not optimal due to the polarization dependence of NLC and FLC devices. Today, the rapid maturity of microelectromechanical system (MEMS) fabrication techniques and devices has opened up many new possibilities for MEMS-based optical systems such as optical disk pickup heads, femtosecond autocorrelators, spatial light modulators, optical scanners, and fiber optic switches.[4] The advantages of micromachined-based optical switches include polarization independence, high isolation, compactness, and low power consumption. In addition, MEMS technology presently promises to be the featured choice for a space-based environment compared to other switch technologies.[5] Integrated optics MEMS switch architectures have been proposed that include an electrostatically driven micromechanical 2×2 optical switch,[6] an electrostatically actuated integrated optical nanomechanical wavelength-dependent directional switch,[7] and the integration of membrane type deformable mirror devices with optical wavelengths to form a 2×2 single-mode optical fiber switches.[8] MEMS-based free-space 2×2 fiber optic switch architectures were also proposed using micromachined piezoelectric thin-film microactuators.[9–11] A $1\times N$ fiber optic switch was demonstrated using $x-y$ mechanical deflection via two rotating prisms and a fixed mirror.[12] An 8×8 matrix free-space MEMS optical switch utilizing free-rotating hinged mirrors was also demonstrated.[13] More recently, a 2×2 fiber optic switch array that can be cascaded based on a Banyan network to form an $N\times N$ optical switch has been proposed using a two-dimensional digital micromirror device[14] (2D-DMD). Another key component to enhance the versatility of the current wavelength-division multiplexing (WDM) technology for high-data-rate optical communications is the programmable multiwavelength optical add-drop switch. Several approaches have been proposed to realize this add-drop switch, including two designs using one-dimensional[15] (1-D) and two-dimensional[16] (2-D) MEMS-based tilt-type mature micromirror technology. Note that the 2D-DMD is also used to realize a fault-tolerant polarization-insensitive variable photonic delay line[17] and a multiwavelength variable optical attenuator.[18] Future large-scale optical networks will deploy $N\times N$

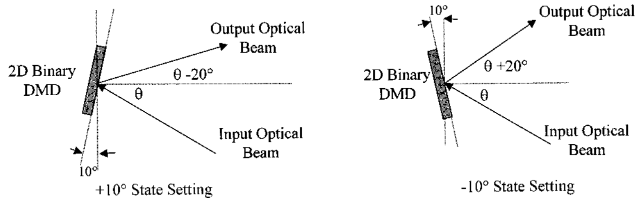

Fig. 1 Binary operations (+10- and −10-deg states) of a micromirror.

switch matrices where wavelengths from any input fiber can be routed to any output fiber. Current MEMS-based add-drop switches[15,16] cannot perform this task as their structures do not form a 2×2 switch that can be further interconnected to form a large-switch matrix. Specifically, light input from the add port cannot exit from the drop port.

Hence, in this paper we extend the concepts outlined in Refs. 14 and 16 to realize, perhaps for the first time, how small-tilt micromirrors can be used to form a three-dimensional (3-D) 2×2 optical switching array for implementing the all-important large $N \times N$ type switch matrix. Then we extend this 2×2 fiber optic switch concept to form the multiwavelength 2×2 fiber optic switch for current WDM optical networks. The rest of the paper describes our approaches the presents a proof-of-concept demonstration.

2 Micromirror-Based Fault Tolerant 2×2 Fiber Optic Switch Structure

For our experiment, the small tilt MEMS-based micromirror device is the VGA format 2-D DMD designed by Texas Instruments (TI) for display applications. The TI 2D-DMD environmental test data is based on the military standard 883D, indicating that perhaps it can provide robustness for a space-based environment.[19] The TI 2D-DMD has half a million micromirrors. Each micromirror is 16×16 μm, the intermirror gap is 1 μm, and pixel pitch is 17 μm. Each micromirror has a 15-μs switching speed, and the device has a ~62% optical efficiency.[20] The device has two states of operation, i.e., +10 and −10 deg, as shown in Fig. 1. When the optical beam is incident on the +10-deg state setting of the micromirror at an angle of θ, it is reflected at an angle of $\theta-20$ deg. Conversely, the optical beam is reflected at angle of $\theta+20$ deg when the corresponding micromirror is set to the −10-deg state. Using this geometrical optics approach, our first proposed 2D-DMD-based 2×2 fiber optic switch architecture is shown in Fig. 2, where the input optical beams are normally incident onto the 2D-DMD, and macropixels 1 and 2 are operated in orthogonal mode. Keeping in mind that the minor mechanical vibrations that are common with a free-space design can disrupt the operation of MEMS-based devices, it would be desirable to have a fault-tolerant optical switch structure. As shown in Fig. 3, we propose to use several micromirrors

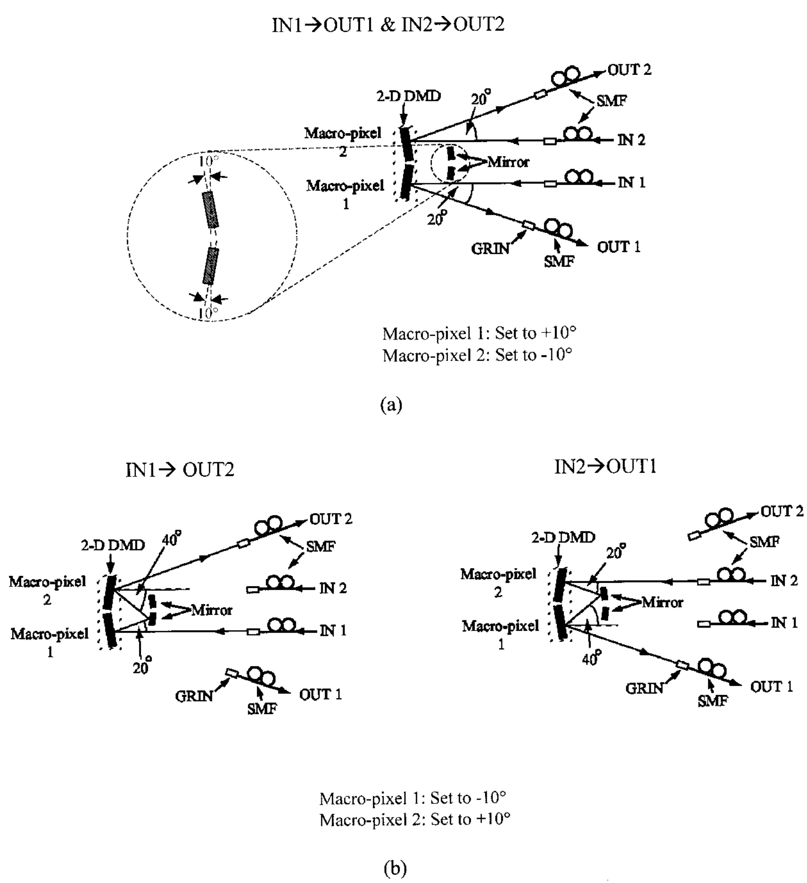

Fig. 2 Proposed small-tilt micromirror-based 2×2 fiber optic switch using a fixed mirror pair: (a) switch straight state operation and (b) switch exchanging state operation.

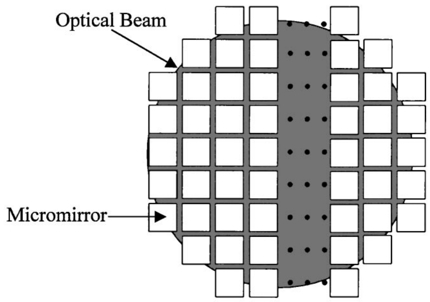

Fig. 3 Macropixel layout for fault-tolerant design approach.

called macropixels to control an optical beam. The null-to-null optical beam diameter of a standard fiber optic graded-index (GRIN) lens output is larger than the size of an individual micromirror. For example, there are about 435 micromirrors in each macropixel for a 0.4-mm full width half maximum (FWHM) optical beam from the GRIN lens coupled fiber. This implies that there is no catastrophic signal loss when a partial micromirror failure in a macropixel occurs, leading to the fault tolerant switch design. In this way, we define the failure rate (FR) as the ratio of the number of failed micromirrors to the number of micromirrors per beam to characterize the fault tolerance. For example, if the FR is 0.1, i.e., the number of micromirrors per beam is 100, then the number of failed micromirrors is 10. This also indicates that the accumulated optical loss is ~10%. However, this relatively small accumulated optical loss can be compensated by using optical amplifiers or optical equalizers in the fiber optic network. Figure 2(a) shows the switch straight state operation where the signals from IN1 and IN2 are sent to OUT1 and OUT2, respectively. In this case, the macropixel 1 is set to the +10-deg state and macropixel 2 is set to the −10-deg state. Macropixel 1 reflects the optical beam from IN1 to OUT1, while macropixel 2 reflects the optical beam from IN2 to OUT2. On the other hand, when macropixel 1 is set to the −10-deg state and macropixel 2 is set to the +10-deg state, the exchanging state operation shown in Fig. 2(b) can be realized with the help of a fixed mirror pair specially placed between paths of two input optical beams and orientated at angle of 10 deg with respect to the vertical axis. The optical beam from IN1 is sent to OUT2 by reflecting at macropixel 1, a fixed mirror, and macropixel 2. Meanwhile, by the reflecting at macropixel 2, a fixed mirror, and macropixel 1, the optical beam from IN2 is sent to OUT1. For tightly packed 1.8-mm-diameter GRIN lenses, a 10-mm-wide 2D-DMD with a 6.5-mm macropixel pitch, and 1.1-mm-diam fixed mirrors, the fiber GRIN-DMD distance and the fixed mirror-DMD distances are geometrically found to be 8 mm, indicating that optical beams from IN1 and IN2 suffer the same free-space optical paths for each switch setting. Note that the fixed mirror pair can be located on a single MEMS chip with 2 large pixels, one permanently set to a −10-deg tilt and the other also permanently set to a +10-deg tilt, thus forming a compact switch package with electronic alignment of beams. This is because the tilt mirror positions respond in an analog fashion to applied voltage.

Our alternative 2D-DMD-based 2×2 fiber optic switch structure where fiber interconnections are specially located is shown in Fig. 4. In this architecture, both macropixels

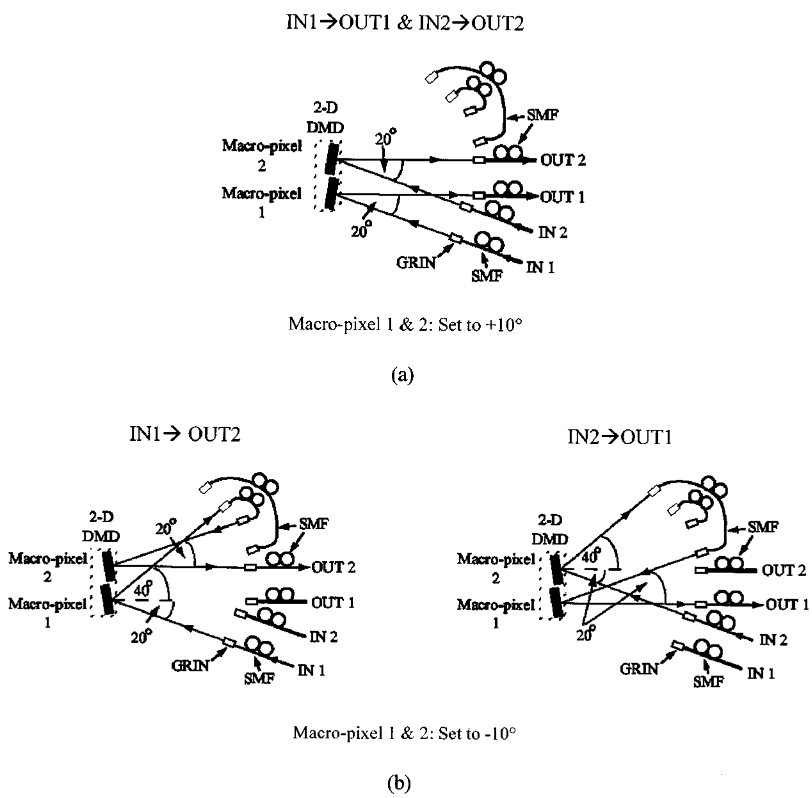

Fig. 4 Our alternative proposed small-tilt micromirror-based 2×2 fiber optic switch using fiber interconnections: (a) switch straight state operation and (b) switch exchanging state operation.

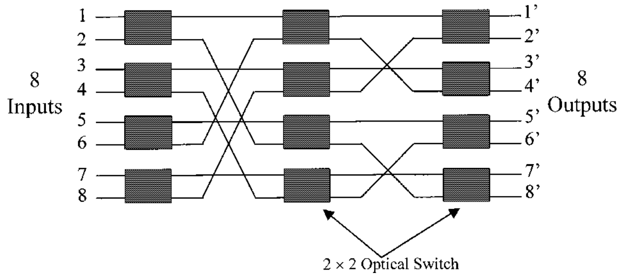

Fig. 5 Eight in eight out Banyan network for forming a large-scale 8×8 optical cross connect.

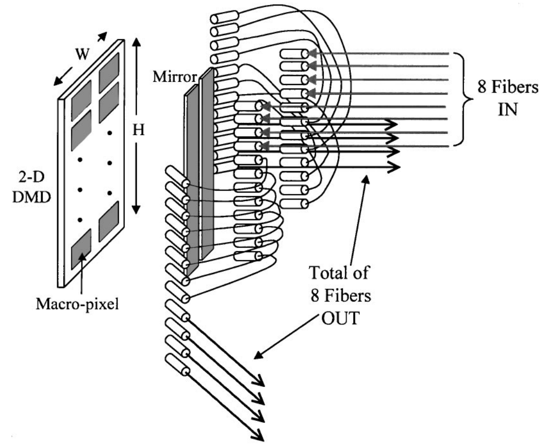

Fig. 6 Combination of a 2D-DMD and tightly packed GRIN lenses to form 12 compact fixed mirror-pair-based 2×2 fiber optic switch modules, leading to an eight in eight out Banyan network.

are set to the same state of operation and optical beams are incident on the DMD at the angle of 20 deg with respect to the horizontal axis. Compared to the Fig. 2 design, this design provides better flexibility for placement of the optical fibers, although at a higher loss penalty. In other words, the fixed mirror pair misalignment used in Fig. 2 can lead to catastrophic failure in switch operation. With fiber collimators, each end of the optical fiber can be aligned separately by using the mechanical tweeker technique, thus providing more degrees of freedom and flexibility to place the optical fibers. Recently, this method was demonstrated to align an array of 33 GRIN lenses in the 7-bit photonic controller for a phased-array radar.[21] Figure 4(a) shows the straight state of operation in which both macropixels are set to the -10-deg state. In this way, by reflecting at macropixels 1 and 2, the optical beams from IN1 and IN2 travel to OUT1 and OUT2, respectively. To exchange the state of operation, both macropixels are set to the $+10$-deg state, as shown in Fig. 4(b). The optical beam from IN1 goes to OUT2 by reflecting at macropixel 1, traveling through the optical fiber, and reflecting at macropixel 2. Similarly, the optical beam from IN2 is sent to OUT1 by reflecting at macropixel 2, traveling through the optical fiber, and reflecting at macropixel 1. A fiber GRIN-DMD distance of 13.3 mm is geometrically found for tightly packed 1.8-mm-diam GRIN lenses and a 6-mm-wide 2D-DMD with a 2.7-mm macropixel pitch so that the optical beams from IN1 and IN2 suffer the same amount of free-space delay for each switch setting.

As mentioned earlier, the 2×2 optical switch is a building block to implement a large-scale $N\times N$ optical switch. Our 2D-DMD-based 2×2 fiber optic switch structures based on the use of a fixed mirror pair and specially located fiber interconnections can be used to realize a compact $N\times N$ optical switch. For instance, based on an eight in eight out Banyan network, as shown in Fig. 5, a combination of either a 10×22-mm [width (W)×height (H) in Fig. 6] 2D-DMD for our fixed mirror pair-based switch architecture or a 6×22-mm (W×H in Fig. 6) 2D-DMD for our spatially located fiber interconnection-based switch structure with tightly packed 1.8-mm-diameter GRIN lenses can be used to build 12 compact 2×2 fiber optic switch modules. Clearly, because of the flexibility the optical fiber enables us to arrange and connect two optical fibers together, these 12 compact switch modules can be connected together to form a eight in and eight out Banyan network, as shown in Fig. 6. This 3-D package can have a typical 3×3×6 cm volume. Furthermore, for robust packaging, the free-space volumes can be replaced by solid-optic forms for greater robustness.

3 Multiwavelength Small-Tilt Micromirror-Based 2×2 Fiber Optic Switch Architecture

Figure 7 shows our proposed multiwavelength 2×2 fiber optic switch structure using highly mature and robust small-tilt micromirrors. The key innovation is the use of a specially located fixed mirror to form a symmetric 2×2 retroreflective switching structure, where although the mirror tilt angles are small, the beam deflection angles are large, leading to ease in placement of input-output fiber optics. Figures 8(a) and 8(b) describe the two states of operations of our multiwavelength small-tilt micromirror-based 2×2 fiber optic switch using a geometrical optic approach. Figure 8(c) shows the geometrical design diagram of our tightly packed 2×2 retroreflective switching switch structure. A compact distance d of 14.7 mm is calculated when using the 10.88×8.16-mm size VGA format 2D-DMD from TI. As shown in Fig. 7, the multiwavelength optical beams from IN1 and IN2 enter the three-port optical circulators and are then demultiplexed by fiber coupling

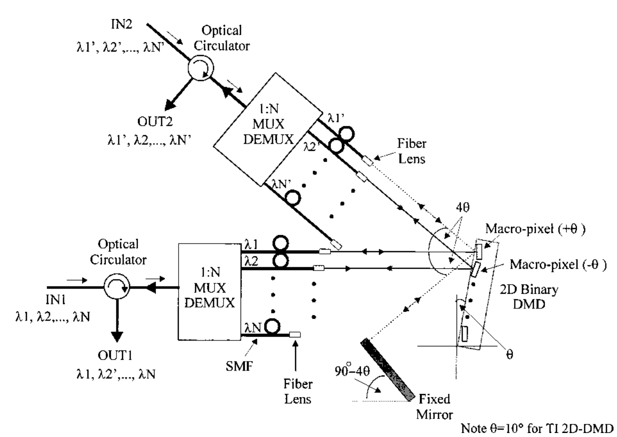

Fig. 7 Proposed multiwavelength small-tilt micromirror-based 2×2 fiber optic switch.

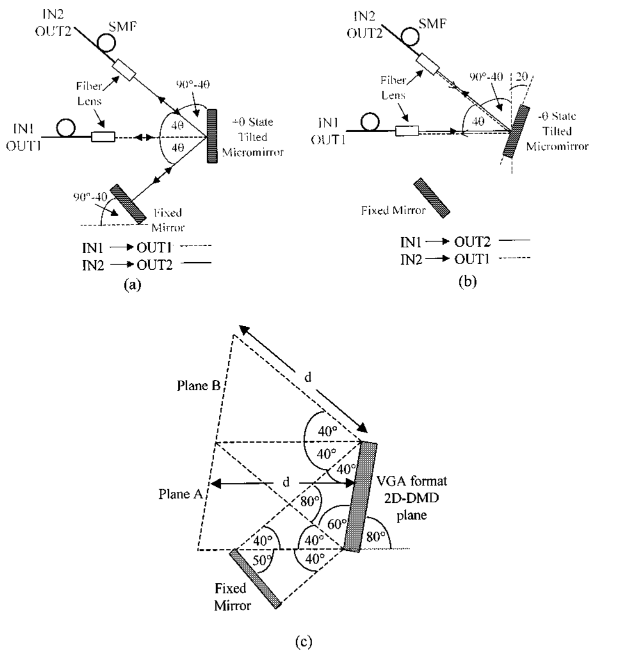

Fig. 8 Geometrical optics explanation of our multiwavelength small-tilt micromirror-based 2×2 fiber optic switch operations: (a) straight state operation, (b) exchanging state operation, and (c) diagram of a tightly packed switch structure.

WDM multiplexing/demultiplexing (MUX/DEMUX) devices. The output ports of each WDM MUX/DEMUX device are arranged so that the optical interchannel crosstalk and packaging are optimized. Each optical beam from the output ports of a WDM MUX/DEMUX device are incident on a different zone of the 2D-DMD. Note that in this architecture, only one macropixel is used to control an individual wavelength optical beam (e.g., λ1′s) from IN1 and IN2 ports and the 2D-DMD chip is tilted by 10 deg with respect to the vertical axis. When the macropixel associated with the desired wavelength optical beam is set to the +10-deg state (see λ1 and λ1′ paths), the λ1 optical beam from IN1 is reflected back to its output port of a WDM MUX/DEMUX device. After multiplexing and passing through the three-port optical circulator, the λ1 optical beam is now at OUT1. Similarly for the λ1′ optical beam from IN2, after passing to the three-port optical circulator and WDM demultiplexer, the λ1′ optical beam from IN2 is incident at an angle of 40 deg on the same macropixel as the λ1 optical beam from IN1. Then it is reflected at the same angle and normally incident on a fixed mirror, which is oriented at an angle of 50 deg with respect to the horizontal axis. In this way, the λ1′ optical beam is reflected back to its previous path and goes to OUT2 by passing through the three-port optical circulator. On the other hand, when the micromirror is set to the −10-deg state (see λ2 and λ2′ paths), the λ2 optical beam from IN1 is reflected from the corresponding macropixel at an angle of 40 deg with respect to the horizontal axis. Then it goes to the corresponding output port of another WDM multiplexer. After multiplexing and passing through the three-port optical circulator, the λ2 optical beam from IN1 is now at OUT2. Likewise, the λ2′ optical beam from IN2 is sent to OUT1 at the same time.

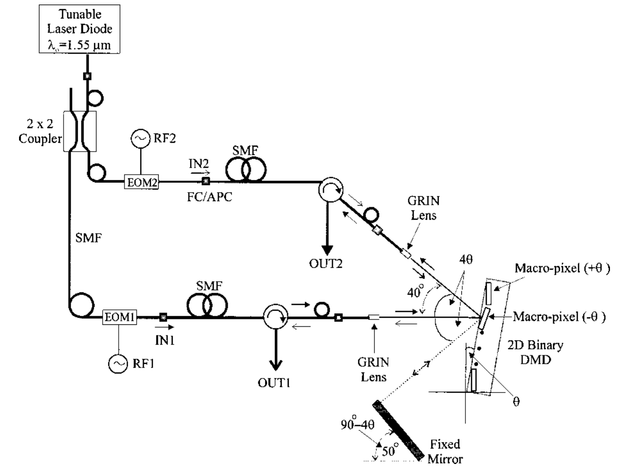

Fig. 9 Our experimental proof-of-concept demonstration of our multiwavelength small-tilt micromirror-based 2×2 fiber optic switch.

4 Multiwavelength Small-Tilt Micromirror-Based 2×2 Fiber Optic Switch Experimental Demonstration

The experimental setup of our multiwavelength small-tilt micromirror-based 2×2 fiber optic switch is shown in Fig. 9. We use a tunable laser diode with a center wavelength of 1550 nm from Santec Corp. The output of the tunable laser is directly connected to a fiber optic 2×2 coupler to simulate two laser sources. The light from one output port of the 2×2 coupler is modulated with an 18-kHz square wave by using the combination of a 90 deg FLC cell and two polarizers (EOM1 in Fig. 9). This modulated light is then fed to IN1 port. Light from the other output port of the 2×2 coupler is modulated with an 18-kHz analog wave from a WaveTek signal generator by using an electro-optic modulator from Uniphase Corp. (EOM2 in Fig. 9). This modulated light beam is then fed to IN2. Figure 10 show a view of the experimental setup where the fiber GRIN-DMD distance is ∼3.9 mm and the DMD-fixed mirror distance is ∼18.6 mm. The WDM MUX/DEMUX devices are not used in the experiment. Note that all fiber connectors and adapters are FC/APC to reduce the back reflections (>50 dB) from the inserted components.

Figure 11 shows the switch binary operation traces. The first two traces from top are the RF signals at OUT1 and OUT2 ports for the straight state of operation

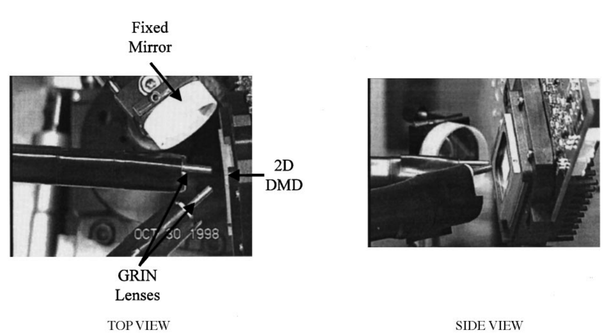

Fig. 10 Views of our multiwavelength small-tilt micromirror-based 2×2 fiber optic switch experimental demonstration.

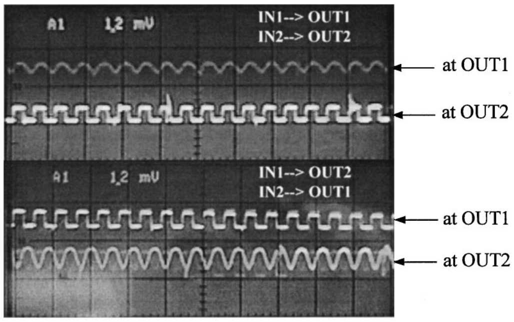

Fig. 11 Switch binary operation traces. First two traces from top are for switch straight state operation and the last two traces are for switch exchanging state operation.

(IN1→OUT1, IN2→OUT2) while the last two traces are for the exchanging state of operation (IN1→OUT2, IN2→OUT1).

The measured average optical loss of our multiwavelength 2×2 fiber optic switch is 14.8 dB at the 1.55-μm operating wavelength. This average optical loss value is limited by several loss numbers of the different components such as the visible design TI 2D-DMD (6.43 dB), two three-port optical circulators (1.21 dB), fiber adapters (1.14 dB), and free-space to fiber coupling (4.45 dB). Substantial loss improvements for an optimized loss of <8 dB are possible using larger gold-coated (>95% reflectivity) micromirrors to reduce the device diffraction effect and increase the device fill factor, an IR antireflection-coated hermetic optical window for the device, imaging optics with an f-number>2.8, and spliced fibers instead of using fiber adapters. To select the appropriate size of the micromirror, we must first analyze the device diffraction effect as follows. The separation angle θ between nearby diffraction order light beams caused by the 2D-DMD in the far-field observation zone is $\lambda/\Delta d$ rad, where Δd is the inter pixel distance (e.g., 17 μm) and the device fill factor is $(16/17)^2 = 0.88$, where the square pixel has a 16-μm side. For the visible wavelength operation, e.g., λ=632.8 nm, θ is 37.22 mrad or 2.13 deg, while θ is 91.18 mrad or 5.22 deg for a 1.55-μm operating wavelength. Therefore, for device operation equivalent to the visible band device design (i.e., θ=2.13 deg), the size of a micromirror for the 1.55-μm operating wavelength should be at least 41×41 μm with a 1-μm interpixel gap. As a result, a better fill factor of >0.95 can be obtained and the device diffraction effects are similar to those of the optimal case of the visible wavelength device design. In this way, the expected 1550-nm-band 2D-DMD optical loss is designed to be <2.08 dB (>62% optical efficiency).

However, the macropixel-approach-based TI 2D-DMD loss of 2.08 dB and the 4.45 dB free-space-to-fiber coupling efficiency in the structure are still the main factors that limit our 2×2 switch loss performance. One way to compensate for this moderate optical loss is to use optical amplifiers. Another way is to further reduce the TI 2D-DMD loss and increase the free-space-to-fiber coupling efficiency. This can be done by using only one rather than several micromirrors (or a macropixel) to perform the switching operation. In this case, the size of the single micromirror can be estimated as follows. Consider the beam waist of an optical beam from a GRIN lens focused on to the 2D-DMD by an external focusing lens that is stacked adjacent to the GRIN lens output surface. The measured beam waist at the plane of a GRIN lens is[22] 0.23 mm. From Fig. 8(c), the geometrically calculated distance d between plane A (or B) and the 2D-DMD plane is 14.7 mm, indicating that a focusing lens with a focal length of 14.7 mm can be used to focus the GRIN lens exiting optical beam onto a micromirror. In this case, the beam waist or beam radius at the micromirror plane can be determined to be[23]

$$w(z)=\left\{\frac{\lambda z_{01}}{\pi}\left[\left(\frac{1-z_m}{f}\right)^2+\left(\frac{z_m}{z_{01}}\right)^2\right]\right\}^{1/2}, \qquad (1)$$

where $w(z)$ is the beam waist at the distance z, $z_{01} =(\pi w_{01}^2)/\lambda$, w_{01} is beam waist at the GRIN lens output plane, f is the focal length of the focusing lens, and $z_m =f/[1+(f/z_{01})^2]$. For λ=1.55 μm and f=14.7 mm, the minimum spot size can be found at $z=z_m=14.4$ mm and the beam waist or beam radius is calculated to be 32 μm. This 64-μm beam diameter value indicates that an array of 80- ×80-μm micromirrors can be used, where each beam interacts with its specified single micromirror. In this way, the optical loss due to the 2D-DMD essentially depends on only the reflectivity of the micromirror material, e.g., Au reflectivity ~95% at the 1.55-μm operating wavelength gives a 2D-DMD optical loss of 0.22 dB. Furthermore, using the single-micromirror approach, the light coupling using GRIN lenses becomes highly efficient, reducing the optical loss to a typical GRIN lens-fiber coupling loss of 0.6 dB (Ref. 21). Hence, using the single-mirror approach an improved average optical loss of <2.33 dB of our 2×2 switch structure can be achieved. This improved average optical loss is due to the reflectivity of the gold-coated single micromirror (0.22 dB), the double-passage light propagation via a three-port optical circulator (1.21 dB), spliced fibers (0.3 dB), and the free-space-to-fiber coupling loss (0.6 dB). Note that although the optical loss of our 2×2 switch structure is improved, the fault-tolerant switch design approach is eliminated when using the single-mirror beam-switching approach.

Another system performance issue is the coherent or homowavelength optical crosstalk due to the leaking light coming from the various components at the chosen operating wavelength. Typically, a low crosstalk level of −40 dB is more than sufficient for optical switches used in WDM applications to obtain low bit error rate.[24] Figure 12 shows the measured optical coherent crosstalk from the 1550- to 1590-nm operating wavelength of our structure, indicating an average coherent crosstalk of −22 dB with ±0.9 dB fluctuation. Lower crosstalk levels can be obtained by improving the on-off ratio of the 2D-DMD used in our switch structure.

5 Conclusion

We proposed the use of small-tilt micromirrors to form 2×2 fiber optic switch array structures. Two approaches based on the use of a fixed mirror pair and fiber interconnection have been introduced. With the SXGA format T1 2D-DMD, tightly packed GRIN lenses, and the flexibility

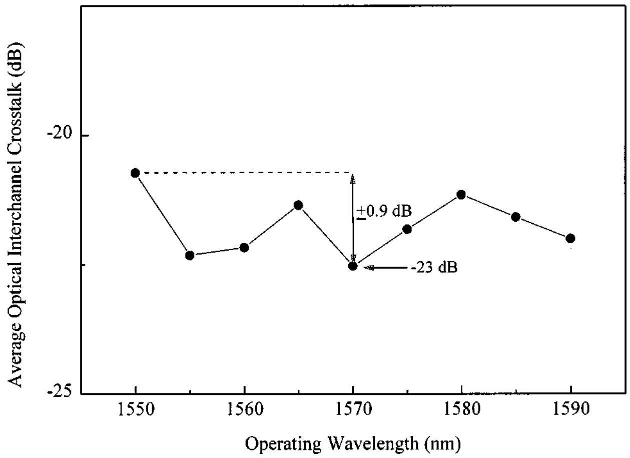

Fig. 12 Measured optical interchannel crosstalk versus operating wavelength, indicating the average optical interchannel crosstalk of -22 dB and ± 0.9 dB fluctuation over 40 nm.

of the optical fiber, 12 compact 2×2 fiber optic switch modules can be implemented, leading to a eight in eight out Banyan network. A multiwavelength 2×2 fiber optic switch based on this small-tilt micromirror approach was proposed and a proof-of-concept experiment was demonstrated. The average optical loss for this switch is 14.8 dB, limited by visible design TI 2D-DMD, the three-port optical circulators, fiber adapters, and the free-space-to-fiber coupling efficiency. The measured average optical coherent cross-talk is -22 dB with ± 0.9 dB fluctuation over 40 nm. The number of 2×2 fiber optic switch modules as well as the number of operating wavelength relies on the area of the 2D-DMD active region and the size of the null-to-null optical beam diameters at the micromirror plane. Future work relates to optimization of our switch structures for telecommunication IR wavelengths. In particular, the 2D-DMD must be redesigned for the IR band.

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